

# SUBNANOSECOND HIGH-POWER PERFORMANCE OF A BISTABLE OPTICALLY CONTROLLED GaAs SWITCH

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## ABSTRACT

Recent subnanosecond-opening results of the Bistable Optically controlled Semiconductor Switch (BOSS) are presented. The processes of persistent photoconductivity followed by photo-quenching have been demonstrated in copper-compensated, silicon-doped, semi-insulating (GaAs:Si:Cu). These processes allow a switch to be developed that can be closed by the application of one laser pulse ( $\lambda = 1.06 \mu\text{m}$ ) and opened by the application of a second laser pulse with a wavelength equal to twice that of the first laser. The opening phase is a two-step process which relies initially on the absorption of the  $2.13\text{-}\mu\text{m}$  laser and finally on the recombination of electrons in the conduction band with holes in the valence band. The second step requires a sufficient concentration of recombination centers in the material for this process to occur in the subnanosecond regime. This report discusses the effects of 1-MeV neutron irradiation on the BOSS material for the purpose of recombination center generation. Initial experiments indicated a reduction of the recombination time from several nanoseconds down to about 180 ps. Both experimental and theoretical results are presented.

## I. INTRODUCTION

Photoconductive switches made from semi-insulating (SI) GaAs were proposed in the late 1970's for use as both closing and opening high-power switches [1]. Closing was achieved by exciting electrons from the valence band into the conduction band using a laser with a photon energy greater than that of the bandgap. An alternative method to direct excitation across the bandgap was proposed by Schoenbach, et al. [2]. This concept, which is called the Bistable (or bulk) Optically controlled Semiconductor Switch (BOSS), relies on persistent photoconductivity followed by photo-quenching to provide both switch closing and opening, respectively. Persistent photoconductivity results from the excitation of electrons from the deep copper centers found in copper-compensated, silicon-doped, semi-insulating GaAs (GaAs:Si:Cu). The small cross-section for electron capture back into the Cu centers allows long conduction times (tens of microseconds) after the first laser pulse is terminated. Photo-quenching is accomplished by the application of a second laser pulse of longer wavelength which elevates electrons from the valence band back into the copper levels. This laser pulse floods the valence band with free holes which rapidly recombine with free electrons to quench the photoconductivity over a time scale given by the electron-hole lifetime of the material. These processes allow a switch to be developed which can be closed by the application of one laser pulse ( $\lambda \approx 1 \mu\text{m}$ ) and opened by the application of a second laser pulse with a wavelength about twice that of the turn-on laser.

Recent experimental results have shown that the current through a BOSS switch could not be fully quenched by the application of a 140-ps (FWHM)  $2.13\text{-}\mu\text{m}$  laser pulse [3]. A preliminary examination of the semiconductor rate equations indicated that the primary cause for incomplete photo-quenching was that the concentration of the recombination centers was too low. As stated above, the opening transient is the result of a two-step process. The second step is controlled by the electron-hole recombination lifetime which is dominated by the concentration of mid-gap recombination centers (RC) in the bulk material. A defect is considered a RC when the cross-sections for electron and hole capture are approximately equal. Usually, these centers are found near the middle of the bandgap. In this report we examine the effects of varying the RC concentration, by fast-neutron irradiation, on the opening transient of the BOSS switch.

The effects of neutron irradiation on semiconducting materials have been studied for many years [4],[5]. A more recent effort has concentrated on the reduction of the minority-carrier lifetime in GaAs through fast-neutron irradiation [6]. This work directed us towards the investigation of neutron damage for the purpose of RC enhancement in a BOSS device. The time integral of the neutron flux, called the *fluence*, has the units of neutrons/cm<sup>2</sup>. The neutron sources that were used in this work are Sandia National Laboratory's (SNL) SPR-III reactor operating in the pulsed mode and the Annular Core Research Reactor (ACRR). The energy spectrum for these sources is peaked at about 1 MeV [7].

The interaction of fast neutrons with GaAs, and most other target materials, is dominated by elastic nuclear scattering. The total scattering cross section  $\sigma$  is so small, of the order of  $10^{-24}$  to  $10^{-23}$  cm<sup>2</sup>, that the mean free path  $\lambda_p$  in GaAs with a solid-state density  $\rho$  of  $4.42 \times 10^{22}$  cm<sup>-3</sup> [8] becomes, according to the classical kinetic theory of gases

$$\lambda_p = \frac{1}{\rho \sigma} \approx 2.3 + 23 \text{ cm}. \quad (1)$$

This means that fast neutrons will suffer at most one collision in the sample before emerging [9]. This one collision will result in the displacement of either a Ga, As, or impurity atom from its initial site with a recoil energy large enough to initiate a displacement cascade. The primary knock-on atom can have sufficient energy to create literally hundreds of defects in the crystal [10].

## II. SAMPLE PREPARATION

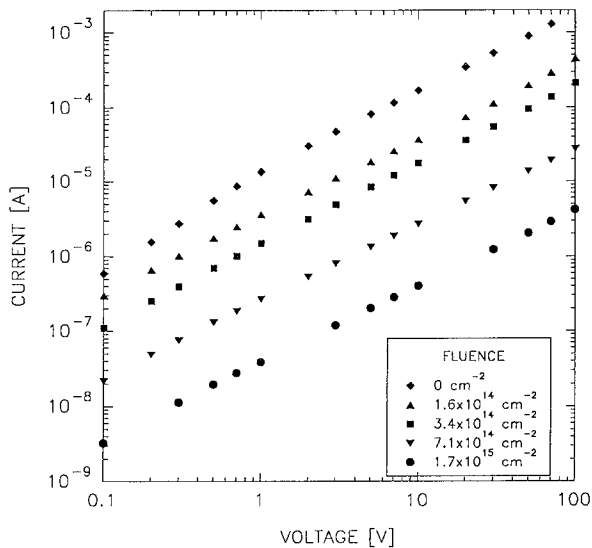
Low resistivity, silicon-doped (n-type) GaAs can be made semi-insulating by the introduction of copper acceptor levels through a thermal-diffusion process (see Ref. [11]). The sample dimensions were 12 mm by 10 mm by 0.44 mm thick.

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After processing the material, the samples were irradiated with fast neutrons to increase the RC concentration. Thus far two sets of BOSS devices have been irradiated at SNL. The first set was irradiated in the SPR-III reactor operating in the pulsed mode prior to the fabrication of the electrical contacts. To achieve higher neutron fluences, the second set of devices were irradiated in the ACRR. To avoid excessive heating, the second set of devices were irradiated in three separate exposures. The sample temperature was held below 100°C during both sample runs. The second group of samples were irradiated in the ACRR after the contacts were fabricated. The  $p^+i-n^+$  devices were manufactured by depositing ohmic contacts that were 1 cm wide and separated by a 5-mm gap on the same side of the sample. After deposition, the contacts were annealed at 450°C for 5 minutes in  $N_2$  at atmospheric pressure.

In the first run (SPR-III) the effect of neutron irradiation on the BOSS material was characterized by using four neutron fluences:  $1.74 \times 10^{15} \text{ cm}^{-2}$  for Group I;  $7.08 \times 10^{14} \text{ cm}^{-2}$  for Group II;  $3.43 \times 10^{14} \text{ cm}^{-2}$  for Group III; and  $1.61 \times 10^{14} \text{ cm}^{-2}$  for Group IV. The fluence values are given relative to 1-MeV GaAs-equivalent damage [12]. Following the irradiation, the sample's radioactivity was allowed to decay, for approximately one month, until it was below the background level. The dc I-V characteristics of the samples, shown in Fig. 1, indicate an increase in the switch resistance from about 60 k $\Omega$  for the non-irradiated devices to about 24 M $\Omega$  for the devices irradiated with the highest fluence. Figure 1 shows that neutron irradiation moves the Fermi level towards the middle of the bandgap.



**Fig. 1** Effect of neutron irradiation on the DC I-V characteristics of BOSS devices.

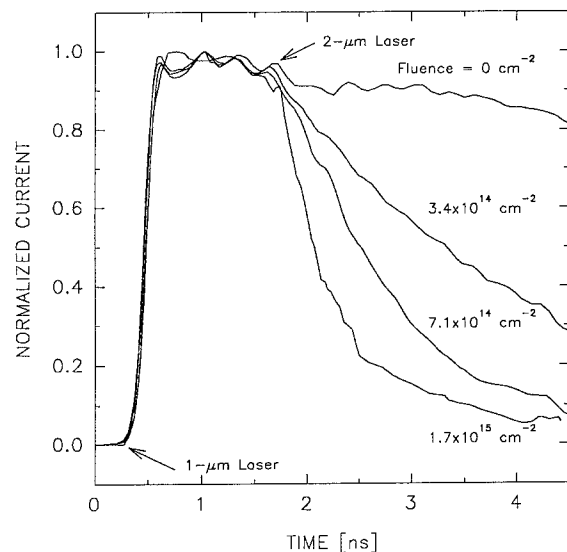
The switching results from the SPR-III run indicated that a higher neutron fluence was necessary to achieve the desired opening performance. Therefore, the second sample run was irradiated at the ACRR because it could more readily reach the desired neutron fluence. Two groups of samples were irradiated at the ACRR:  $5.3 \times 10^{15} \text{ cm}^{-2}$  for Group V, and  $1.8 \times 10^{16} \text{ cm}^{-2}$  for Group VI. To date only the devices from Group V have been investigated. The dc I-V characteristics of these devices indicated that the switch dark resistance was about 100 M $\Omega$ .

### III. SWITCHING EXPERIMENTS

The BOSS-switching experiments were conducted with a mode-locked Nd:YAG laser system (1.06  $\mu\text{m}$ ), manufactured by

Continuum Inc., that was equipped with a optical parametric generator (OPG) that served to double the wavelength (2.13  $\mu\text{m}$ ). The laser system produced a Gaussian pulse with a FWHM of about 140 ps. A simple optical delay was then used to adjust the time between switch closure and when the switch was opened. Photoconductivity measurements were performed to evaluate the operation of the neutron irradiated BOSS devices. The BOSS switches were embedded in a 50- $\Omega$  transmission line (two-way transit time = 4 ns) that was DC charged. The current through the device was measured by a 50- $\Omega$  current-viewing resistor (CVR) placed after the switch in the 50- $\Omega$  line. The current waveform was recorded by a Tektronix SCD5000 digitizer with a 4.5 GHz analog/digital bandwidth. The light was delivered to the switch via a 0.5-inch diameter quartz rod that was polished on the effluent end and had a rough-sanded finish on the end that was illuminated by the laser. This served to remove much of the mode structure in the laser pulse; thereby allowing nearly uniform switch illumination. The back face of the switch was illuminated to prevent shadowing of the bulk material located under the contact metalizations.

#### III.A. SPR-III Devices



**Fig. 2** Effect of neutron irradiation on the opening transient of BOSS devices for several neutron fluences (SPR-III) and non-irradiated material.

The results of the photoconductivity experiments on the devices that were irradiated in the SPR-III are shown in Fig. 2 for three neutron fluences and the non-irradiated material for an applied bias voltage of 50 V. The incident pulse energy for the 1.06- $\mu\text{m}$  laser was 2.1 mJ while the incident pulse energy for the 2.13- $\mu\text{m}$  laser was 5.0 mJ.

As the neutron fluence was increased, the ability of the BOSS device to open was greatly improved. This is direct evidence that neutron irradiation creates recombination centers in GaAs. This also substantiates the earlier findings that indicated the need to increase the recombination center density in order to allow the BOSS switch to open in the subnanosecond regime. For a device in Group I, a curve fit to the switch conductivity during the opening phase, after it was extracted from the load line, indicated a recombination time on the order of 250 ps.

### III.B. ACRR Devices

As stated above, so far only the devices in Group V have been analyzed. Initial photoconductivity measurements on a device in this group indicated that the RC density was too large because the BOSS device would not remain on after the first laser pulse was terminated. Thermal annealing experiments were then conducted to reduce the RC density by annealing out the damage created by the neutrons [13]. The results of the photoconductivity/annealing experiments are shown in Fig. 3. The bottom trace in Fig. 3 is the response of the switch after the copper leads were attached with silver epoxy that was annealed at 110°C for 15 minutes. The inability of the switch to remain closed after the 1- $\mu\text{m}$  laser pulse was terminated was an indication that the electrons that were elevated into the conduction band were recombining with holes in the valence band before those holes could be trapped in the  $\text{Cu}_B$  level.

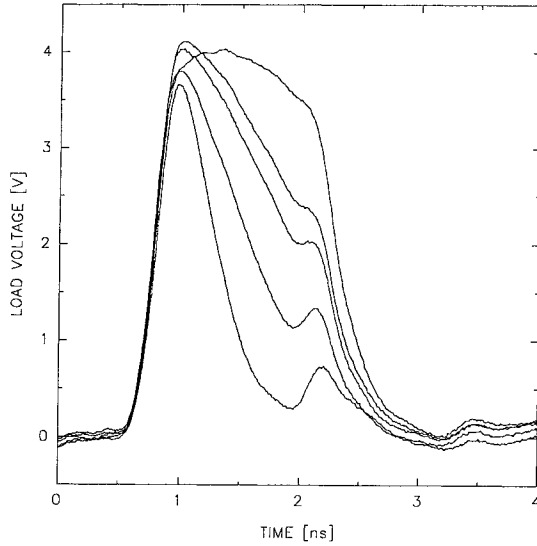


Fig. 3 Voltage across the 50- $\Omega$  CVR for an applied bias of 10 V. Effect of 15-minute thermal anneals on the photoconductivity response of BOSS devices irradiated in the ACRR. From the bottom: 110, 207, 225, 247, and 268°C.

To systematically remove some of the neutron-induced damage, one sample was annealed for 15 minutes at increasing temperatures of 207, 225, 247, and finally 268°C. Both dc I-V and photoconductivity measurements were made between each anneal. The anneals had a negligibly small effect on the dc I-V characteristics. However, the photoconductivity measurements showed a rapid increase in the tail current, or current after the 1- $\mu\text{m}$  laser, with increasing temperature. A curve fit to the switch conductivity, which was extracted from the load line, indicated a recombination time of 180 ps after the 268°C anneal. Initial measurements indicate that the on-state of the switch is in the 10- $\Omega$  regime; clearly too high for any practical pulsed power applications. Efforts are currently being made to reduce the on-state impedance to less than one ohm. Previous high-power switching experiments demonstrated an on-state resistance of approximately 3.5 ohms in non-neutron irradiated BOSS devices [14].

The strong effect that these low-temperature anneals had on the switching performance of BOSS devices indicates that the 450°C contact anneals on the SPR-III samples probably removed some of the neutron damage. Previously reported annealing studies of neutron-irradiated GaAs [15] show one pronounced annealing step at about 200°C and a second, larger step starting

at about 400°C. The effects that we are measuring in the ACRR samples are associated with the first step. However, the contact anneals on the SPR-III samples are in the range of the second annealing step. The actual effect of these steps on the switching mechanism is still under investigation.

It has also been reported that almost all of the neutron-induced defects are annealed out at temperatures between 500°C and 600°C [16]. This was also seen in our work when neutron-irradiated, n-type GaAs was compensated with copper at a diffusion temperature of 575°C. Although the dark resistivity of the sample was in the low megohms, the photoconductivity data indicated that there was no enhancement of the RC density over the non-irradiated material. Therefore, the neutron-induced defects were probably annealed out by the 575°C anneal.

### IV. DEVICE MODELING

In this section we discuss the semiconductor rate equations which are obtained from the continuity equations for electrons and holes, the rate equations for trapping kinetics, the drift-diffusion current equations, and Poisson's equation under the assumptions of spatial uniformity and charge neutrality. These assumptions are valid in the bulk region away from the contacts where the electric field can change rapidly. This is not unreasonable since the samples that were considered in this analysis were fitted with injecting contacts, made from a forward biased  $p^+i-n^+$  structure, which reduce the fields at the contacts considerably. The rate equations consider only the localized concentration of free and trapped charges, therefore, they are only valid under the conditions of low-carrier injection and moderate electric fields.

The transient development of the electron density in the conduction band ( $n$ ), the hole density in the valence band ( $p$ ), and the relative occupation numbers ( $0 \leq r_i \leq 1$ ) of the various deep levels with a given density  $N_i$  is given by the following set of rate equations

$$\begin{aligned} \frac{dn}{dt} &= \dot{n}_{cv} + \sum_i N_i \dot{x}_{ci}, \\ \frac{dp}{dt} &= \dot{n}_{cv} + \sum_i N_i \dot{x}_{vi}, \\ \frac{dx_i}{dt} &= \dot{x}_{vi} - \dot{x}_{ci}. \end{aligned} \quad (2)$$

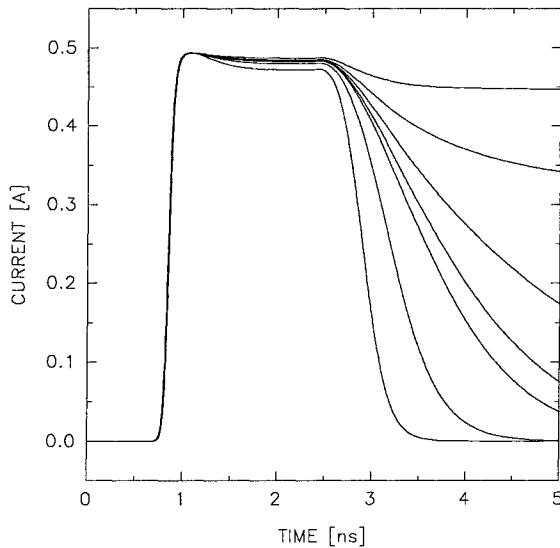
The terms on the right hand side denote the various transitions between the deep levels and the conduction and valence bands that are included in the model. Band-to-band transitions ( $\dot{n}_{cv}$ ) consist of direct recombination and thermal emission, and a contribution from the action of two-photon processes induced by the shorter wavelength laser. The terms describing transitions to and from the deep levels contain the effects of stimulated emission due to the external laser irradiation. Also considered are processes of trapping and spontaneous emission.

The rate equation model included two copper levels ( $\text{Cu}_B$  &  $\text{Cu}_A$ ) which act as deep acceptors, one deep donor level (EL2) which is native to GaAs, and one recombination center (RC). The concentration of the RC level was varied from  $4 \times 10^{15}$  to  $1 \times 10^{16} \text{ cm}^{-3}$  in the analysis to simulate the effect of increasing the neutron fluence. Because the rate equations are zero dimensional, they do not contain any of the circuit parameters in which the BOSS devices are embedded. To facilitate comparison with the experimental results, the values of the calculated electron and hole concentrations are used to determine the overall switch conductivity ( $\sigma$ ) from the following relation

$$\sigma(t) = q(n(t)\mu_n + p(t)\mu_p) [\Omega \cdot \text{cm}]^{-1}, \quad (3)$$

where  $\mu_n$  ( $=2900 \text{ cm}^2/\text{V}\cdot\text{s}$ ) and  $\mu_p$  ( $=400 \text{ cm}^2/\text{V}\cdot\text{s}$ ) are the low-field electron and hole mobilities. Once the switch conductivity is determined, we calculate the switch resistance using a length of  $0.5 \text{ cm}$  and a cross-sectional area of  $0.05 \text{ cm}^2$ . The switch resistance is then placed into a  $100\text{-}\Omega$  load line, with an applied voltage of  $50 \text{ V}$ , to simulate the experiments.

In this section we discuss some of the theoretical results that were obtained with the rate-equation model. Two laser pulses at different wavelengths are used for the optical excitation source. One laser pulse with a photon energy of  $1.165 \text{ eV}$  ( $\lambda=1.064 \text{ }\mu\text{m}$ ) and a peak photon flux of  $1.6 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$  ( $29.9 \text{ MW/cm}^2$ ) is used to turn on the switch and a second laser pulse with a photon energy of  $0.5825 \text{ eV}$  ( $\lambda=2.128 \text{ }\mu\text{m}$ ) and a peak photon flux of  $1.6 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$  ( $14.9 \text{ MW/cm}^2$ ) is used to turn the switch off. The temporal shape of the laser pulse is assumed to be Gaussian with the standard deviation set equal to  $70 \text{ ps}$  in the simulation. The results of the simulations are shown in Fig. 4 where the switch current is plotted as a function of time for seven different RC concentrations. Figure 4 clearly shows that by increasing the RC concentration by a factor of 2.5, the ability of the BOSS switch to respond to the  $140 \text{ ps}$  laser pulse is dramatically improved. The on-state of the switch was not adversely effected until the RC concentration was increased to  $1.0 \times 10^{16} \text{ cm}^{-3}$  as indicated by a reduction in the on-state current. A higher on-state resistance would be more apparent if the electron and hole mobilities were adjusted with the increase in ionized impurity scattering.



**Fig. 4** Simulated current response of a BOSS switch. Recombination center density [ $\times 10^{15} \text{ cm}^{-3}$ ]: (from the top) 4,5,5.5,5.8,6,7,10.

One drawback of an increased RC concentration is that the on-state conductivity will be reduced because electrons in the conduction band will recombine with holes in the valence band before those holes can be trapped in the  $\text{Cu}_B$  center. This process reduces the number of holes that are trapped in the  $\text{Cu}_B$  center which, in turn, reduces the available sites to receive electrons from the valence band during the turn-off laser pulse. The benefits of an increased RC concentration are apparent during the simulated turn-off transient of the switch. The primary consequence of these results is that a compromise has to be reached between the benefits of a high RC density for the turn-

off transient, and the repercussions of a lower on-state conductivity.

## V. CONCLUSION

Experiments were performed to determine the effect of irradiating BOSS material with several different 1-MeV neutron fluences. One effect was that the Fermi level was moved towards the middle of the bandgap, thereby increasing the off-state resistivity of the devices. Simulation studies were performed on the effect of increasing the recombination center density on the BOSS switching cycle. The semiconductor rate equations were solved showing that by increasing the recombination center density, the BOSS switch could be opened in as little as several hundred picoseconds. The theoretical results were in qualitative agreement with the experimental results which showed that by increasing the neutron fluence, the photo-quenching effect could be enhanced. These results support the claim that fast-neutron irradiation creates deep levels in the middle of the bandgap and that these levels function as fast recombination centers. Further work will be necessary to find the optimum set of parameters that result in a BOSS device that can be opened in  $100 \text{ ps}$  and still have a sufficiently low on-state resistance.

## REFERENCES

1. G. Mourou and W. Knox, *Appl. Phys. Lett.*, vol. 35, p. 492, 1979.
2. K.H. Schoenbach, V.K. Lakdawala, R. Germer and S.T. Ko, *J. Appl. Phys.*, vol. 63, p. 2460, 1988.
3. M.S. Mazzola, R.A. Roush, S.F. Griffiths, D.C. Stoudt, and D.H. Keil, *Proc. 20<sup>th</sup> Power Mod. Symp.*, Myrtle Beach, SC, p. 266, 1992.
4. V.S. Vavilov, 1963, Effects of Radiation on Semiconductors, Translation by the Consultants Bureau Enterprises, Inc., New York.
5. L. Borghi, P. De Stefano, and P. Mascheretti, *J. Appl. Phys.*, vol. 41, no. 11, p. 4665, 1970.
6. C.L. Wang, M.D. Pocha, J.D. Morse, and M.S. Singh, *Appl. Phys. Lett.*, vol. 54, no. 15, p. 1451, 1989.
7. Private communication with F. Mitch McCrory, SNL, Reactor Applications Department.
8. S.M. Sze, 1981, Physics of Semiconductor Devices, 2<sup>nd</sup> ed., John Wiley & Sons, New York, p. 850.
9. Chr. Lehmann, 1977, Interaction of Radiation with Solids and Elementary Defect Production, Nort-Holland Pub. Co., Amsterdam, p. 150.
10. F. Larin, 1968, Radiation Effects in Semiconductors, John Wiley & Sons, New York, Chap. 9.
11. D.C. Stoudt, J.S. Kenney, and K.H. Schoenbach, *Proc. 9<sup>th</sup> IEEE Int. Pulsed Power Conf.*, Albuquerque, NM, 1993.
12. P.J. Griffin, J.G. Kelly, T.F. Luera, A.L. Barry, and M.S. Lazo, *IEEE Trans. Nuclear Science*, vol. 38, no. 6, p. 1216, 1991.
13. D.V. Lang, *Inst. Phys. Conf. Ser. No. 31*, p. 70, 1977.
14. D.C. Stoudt, J.S. Kenney, K.H. Schoenbach, R.A. Roush, S. Ludwig, and M.S. Mazzola, submitted to *IEEE Trans. Electron Devices*.
15. L.W. Aukerman, P.W. Davis, R.D. Graft, and T.S. Shilliday, *J. Appl. Phys.*, vol. 34, p. 3590, 1963.
16. R. Coates and E.W. Mitchell, *Adv. Phys.*, vol. 24, p. 593, 1975.